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# A FUNDAMENTAL STUDY OF FATIGUE IN POWDER METALLURGY ALUMINUM ALLOYS

M. J. Koczak and A. Lawley



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## ABSTRACT

Fatigue response in high strength powder metallurgy aluminum alloys is being evaluated; the primary objective is to establish and understand processing-microstructure-fatigue integrity relationships. The program includes stress-controlled low and high cycle response and a determination of crack propagation rates in both air and saline environments. In scope, there are two concurrent phases of research; in one, the combined effects of powder processing mode and cobalt level (0, 0.4, 0.8%) on fatigue are examined while in the other, cobalt level is kept constant (0.4%) but the powder alloy is processed to give differing but known/controlled levels of deformation (material flow) by forging. S-N curves for axial fatigue (R = EQUAL TO 0.1) in air reveal a strong influence of processing mode on life in alloys containing cobalt. Anisotropy in fatigue response is observed for each condition of cobalt level and processing mode examined; the degree of anisotropy is a function of processing mode if cobalt is present. A comparison with ingot metallurgy material confirms that the fatigue strength of the powder processed alloys is equal to or superior than that of the corresponding ingot metallurgy material. Microstructural characterization of fatigue damage is in progress in order to rationalize fatigue response as a function of composition and mode of processing. Plane strain forgings at a fixed cobalt level (0.4%) have been processed to provide a range of strain (flow) levels, and fatigue specimens (S-N and da/dn) cut from the forgings at selected locations.

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## INTRODUCTION

Fully-dense powder processed materials exhibit attractive mechanical property levels. In consequence, this powder metallurgy (P/M) technology is emerging as a direct competitor to conventional ingot metallurgy approaches. Apart from possible economic benefits, these P/M processed materials exhibit finer and more homogeneous microstructures than ingot metallurgy materials. Of direct interest and importance to the Air Force are aluminum and titanium alloys for airframes and nickel-base superalloys in engine applications. Properties of primary importance are strength, fatigue resistance, toughness, creep resistance and stress-rupture.

Adequate strength and ductility are achieved at full-density. In contrast, dynamic response (fatigue resistance or toughness) is dependent on the mode of densification. Thus, in the forging of a powder preform, lateral flow of the material during densification (as opposed to repressing with constraint on material flow) is necessary in order to promote dynamic property levels comparable to those of cast and wrought material.[1-3] The effect is rationalized in terms of integrity of particle bonding; shearing ruptures oxide or other contaminant films thereby allowing virgin metal contact and a sound mechanical bond across collapsed pore interfaces.

Much of the research on P/M processing to full-density has been concerned with ferrous compositions. Recent work however, on high-strength powder-processed aluminum alloys has indicated a similar potential.[4-7] While a detailed and basic understanding of processing-microstructure-mechanical property relationships has been developed for ferrous P/M compositions, such is not the case for the aluminum alloys. The goal of this program is to develop a basic understanding of processing-microstructure mechanical property relationships in P/M processed high-strength aluminum alloys - with particular reference to the fundamentals of response to cyclic loading. Specific areas of study in this program include:

- the relationships between fatigue behavior (high and low cycle response; da/dn), microstructure and alloy chemistry in powder processed high-strength aluminum alloys

- the influence of processing history upon both the fatigue initiation and propagation processes, with particular reference to material anisotropy

- the effect(s) of environment on high and low cycle response and crack propagation (da/dn) rates.

## BACKGROUND

### (i) Stress-Cycling

Buchovecky and Rearick[8] confirmed the beneficial effect of lateral flow on the fatigue resistance of powder-forged fully-dense compositions equivalent to ingot metallurgy 2014 and 6061. Endurance limits in rotating bend fatigue ($R = -1$) were comparable to those of the wrought counterpart. No attempt was made to relate microstructure to fatigue response, or to characterize fatigue damage as a function of number of load cycles.

Lyle and Cebulak[9] and more recently Cebulak et al.[4] demonstrated integrity under cyclic loading in P/M compositions equivalent to the 7075 ingot metallurgy material. S-N curves of the fully-dense material matched or exceeded those of ingot metallurgy material in notched axial fatigue testing; enhancement in the endurance limit of up to 40% was also reported. No correlation with microstructure was attempted.

(ii) Fatigue Crack Propagation

Otto[5,6] studied the influence of alloy composition and processing history on fatigue crack propagation behavior in high-strength 7xxx alloys fabricated from prealloyed atomized powders. Processing routes were identified which appeared to result in crack growth rates considerably lower than those of the corresponding ingot metallurgy material. Response to crack propagation was a function of alloy composition, processing mode and environment. Corbly[7] observed crack growth retardation due to various levels of peak overload. Plastic zone size was measured and the behavior analyzed in terms of an effective stress-intensity concept.

## EXPERIMENTAL PROCEDURE

The fatigue study involves two concurrent phases. Alloy composition and mode of deformation are varied in Phase I. In Phase II, the objective is to evaluate the role of deformation level/mode at a fixed alloy composition.

(i) Phase I

Alloys used in Phase I were obtained from Alcoa; they were taken from the same powder processed forgings used by Otto[5]. Alloy compositions are listed in Table I; the MA87 alloy has a nominal cobalt content of 0.4%. The major difference between MA87 and 7075 is in the replacement of Cr by Co. The latter introduces a fine dispersion of $Co_2Al_9$ which acts as a strengthener and inhibits grain growth, both of which appear to improve stress corrosion resistance.

The prealloyed (air atomized) powder had an average particle diameter ∿13μm. After cold isostatic pressing to 70% theoretical density, the material was hot compacted to full density at 520°C. The compacted billets were then hot upset and open die-forged at 370°C in two modes, Figure 1.

In the A mode, a single upset preceded the draw (hand forging operation); in the ABC mode, the hot compacted billet was given a triple upset prior to the draw. Fiducial orientation directions (L, LT and ST) are superimposed on Figure 1. The above is not a true powder preform forging operation since the material is already at full density when forged. Material was solution heat-treated and aged to a tensile strength in the range 515 to 565 MPa.

Hour glass-shaped fatigue specimens were machined from the A and ABC processed material at the 0, 0.4 and 0.8% cobalt levels and in each of the three orientations, i.e., L, LT and ST. The minimum diameter in the curved gauge section was 3.175 mm. Specimens were mechanically polished with Linde B $Al_2O_3$ and given a final electropolish in a perchloric/acetic acid solution. To-date, tension-tension axial fatigue tests ($R = 0.1$; $\nu = 30$ Hz) have been run in air.

(ii) Phase II

In this phase of the program, all fatigue testing is to be carried out on the MA87 alloy. To this end, a powder billet was hot compacted to full density at the Alcoa Technical Center. This material constitutes the "zero-deformation" condition. Preforms cut from the billet were hot forged by compressing in plane strain with height reductions of 1.5:1 and 2:1 respectively.

In any forging operation that involves friction, the deformation is inhomogeneous. Therefore visioplasticity is being used to determine the deformation distribution in the final forgings. This will permit excising of fatigue specimens of known local deformation. The visioplastic technique involved splitting the preform in a vertical plane (containing the axis of compression and direction of lateral flow) and scribing a grid network (10 mm squares) on the cut (internal) faces. Grid dimensions were then measured after forging to calculate the local strains. A total of twenty preforms have been hot forged at 288°C. The forgings were subsequently solution-treated and aged as in Phase I.

## RESULTS AND DISCUSSION

### (i) Phase I

Optical micrographs illustrating the grain structure in planes perpendicular to the L, LT and ST directions are compared in Figures 2, 3 and 4; Keller's etch was used to delineate grain morphology. These cover each of the six conditions examined, i.e., three cobalt levels and two modes of deformation at each level. Anisotropy of the grain structure is evident with grain elongation parallel to the draw (forging) direction, L, as expected. At this level of resolution no systematic differences have been established as a result of cobalt level and/or processing mode in planes perpendicular to L and ST. In general, the grains are equiaxed in the L-LT plane in all six conditions. Grain size is extremely inhomogeneous, varying from $\sim$2 to 20μm, which is significantly smaller than that of the ingot metallurgy counterpart. Occasionally, original powder particles (13μm dia.) could be identified. A more detailed characterization of the grain structure will be made utilizing transmission electron microscopy; this will enable the $Co_2Al_9$ and oxide particle distributions to be determined - and in turn correlated with fatigue response. A similar characterization of microstructure in powder-processed alloys is being conducted at AFML and comparisons will be made with their observations.

In the first year of the program, axial fatigue testing has been carried out in air. S-N curves are shown in Figures 5, 6 and 7; these are arranged in pairs (i.e. 5(a) and 5(b), etc.) in order to compare the effects of processing mode for each of the three levels of cobalt. The legends in the figures (L, LT and ST) refer to the direction of cyclic axial loading. For a fixed mode of processing (i.e. A or ABC), the effect of cobalt level is seen by comparing Figures 5(a), 6(a) and 7(a) or Figures 5(b), 6(b) and 7(b). In Figure 8 the effect of cobalt level and processing mode are compared for a fixed orientation (L). Finally, Figure 9 compares the effect of processing mode and specimen orientation at a fixed level of cobalt (0.8%).

In the cobalt-free alloy there is little effect of processing mode on S-N behavior, cf. Figures 5(a) and 5(b). However, with 0.4% and 0.8% Co additions, processing mode does influence fatigue response; ABC processing gives superior S-N performance compared to the A processing mode, the effect being most pronounced at the higher (0.8%) cobalt level, cf. Figure 6(a) with 6(b) and Figure 7(a) with 7(b). The effect is seen clearly in the longitudinal orientation (L) from a comparison of Figures 8(a) and 8(b). From these observations it can be concluded that best S-N performance in air is associated with a combination of cobalt additions and ABC processing.

Anisotropy in fatigue response is observed in each of the six combinations of cobalt level and processing mode; in each condition, fatigue strength increases in the order LT to ST to L. The degree of anisotropy between the L, LT and ST directions is relatively independent of cobalt content for A processing, cf. Figures 5(a), 6(a) and 7(a). For ABC processing, the degree of anisotropy increases with increasing cobalt content, cf. Figures 5(b), 6(b) and 7(b). ABC processing of the alloy containing 0.8% Co gives the best S-N response in each orientation; however this combination of cobalt content and processing mode maximizes anisotropy.

The fatigue data have also been normalized in terms of tensile strength (i.e. $\sigma_{max}$/UTS). While this gives rise to small relative shifts between the S-N curves, the generalizations and trends outlined above still hold. A comparison of the present fatigue data with that of ingot metallurgy 7075-T73 in axial fatigue at $10^5$ cycles shows the general superiority of the powder processed alloys (10). In strain-controlled fatigue, Staley (11) has observed a similar fatigue response, measured in terms of life to crack initiation, for P/M 7XXX-T7, P/M 7XXX+Co-T7, and ingot metallurgy 7475-T6 between $\sim 10^3$ and $10^4$ strain cycles. Below and above this cycle range, the powder processed alloys were superior.

Currently axial fatigue tests (in air) are being run in the low-cycle regime, i.e. at stress amplitudes giving failure in $<10^4$ cycles. In the second year of the program, low and high-cycle stress-controlled axial fatigue will be evaluated in a salt environment for the powder-processed alloys in each of the six combinations of cobalt level and processing mode. Concurrently, a systematic study of crack propagation behavior will be initiated.

A detailed microstructural evaluation of fatigue damage in axial fatigue has been initiated and will continue in consort with the various phases of the fatigue testing program. Development of fatigue damage on the free surface is being monitored by optical and scanning electron microscopy. Surface replication techniques are also under evaluation. To characterize fracture surface morphology, a combination of optical and scanning microscopy is in use. Dislocation substructures developed in the fatigue process will be followed by means of transmission electron microscopy. To date, fractographic observations have revealed matrix shear and striations characteristic of the fatigue process. The goal of the total microstructural study is to seek out differences in structure as a function of the combination of cobalt content and processing mode and to relate these differences to fatigue response. Since the material is available in the hot compacted condition (i.e. prior to any forging) this will serve as a 'base-line' for both microstructure and fatigue response.

(ii) Phase II

Visioplasticity observations have been made using the split preform technique. Distortion of the original 10mm square grid during plane strain forging is illustrated in Figure 10. Here the axis of compression is vertical and the axis of lateral flow horizontal; there is no flow of material in the direction perpendicular to the plane of the figure. Average and local plastic strains were calculated from the grid displacements and the results are summarized in Table II; the zero strain preform serves as a base-line. It is clear from the table that large strain variations exist across the forged preform such that the local strains overlap for the two preforms. Local deformation levels (true strains) of 0, 0.3, 0.6 and 0.7 have been selected for the fatigue study, Table II. Thus, the 0.6 strain level will be evaluated for both of the upset conditions.

Preparation of specimens for axial fatigue testing in the L, LT and ST orientations is in progress; these are being cut from the forged preforms at locations where the local strain levels are 0, 0.3, 0.6 and 0.7 respectively. Microstructures associated with these differing levels of deformation are currently being characterized. Similarly, specimens for the crack propagation study will be cut from the forged preforms to give a spectrum of strain levels. The overall size of the forgings mandates the use of a subsize test specimen. Crack propagation tests will first be run to see if the da/dn data correlate with values obtained using a standard compact specimen.

SUMMARY

- The cobalt-free high-strength powder metallurgy alloys show little effect of processing mode on axial S-N response in air.

- Processing mode influences axial S-N response in air with cobalt levels of 0.4 and 0.8%. ABC processing gives better fatigue resistance than A processing; the effect is most pronounced at the higher cobalt level.

- Anisotropy in fatigue response is observed for each condition of cobalt level and processing mode examined. Fatigue life increases in the order long transverse to short transverse to longitudinal orientation.

- The degree of anisotropy is relatively independent of cobalt content for A processing. For ABC processing, the degree of anisotropy increases with increasing cobalt content. At a fixed cobalt level, ABC processing gives a higher degree of anisotropy than A processing.

- Comparison with ingot metallurgy fatigue data shows the general superiority of the powder processed aluminum alloys.

- Microstructural evaluation and characterization of fatigue damage is in progress in order to rationalize the effect of composition and processing mode on fatigue response.

- Plane strain powder forgings of controlled flow level have been processed at a fixed cobalt content (0.8%). Local strain variations have been determined by visioplasticity and specimens for fatigue testing (S-N and da/dn) cut from the forgings at selected locations to give a known spectrum of strains (levels of flow).

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Table I

Composition of Atomized Powders (5)

wt.%

| Si | Fe | Cu | Mg | Zn | Co | Al |
|---|---|---|---|---|---|---|
| 0.05 | 0.07 | 1.44 | 2.33 | 6.62 | 0 | balance |
| 0.05 | 0.09 | 1.53 | 2.44 | 6.38 | 0.33 | balance |
| 0.06 | 0.05 | 1.42 | 2.40 | 6.73 | 0.79 | balance |

Table II

Range of Strains Measured in Plane Strain Forgings

| Original Preform Height (mm) | Average $\varepsilon_h$ | *Local True Strain* Range ($\varepsilon_\ell$) | $\varepsilon_\ell$ for Testing |
|---|---|---|---|
| 114.3 | 0.4 | 0.1 to 0.8 | 0.3 and 0.6 |
| 150.4 | 0.7 | 0.3 to 1.27 | 0.6 and 0.7 |
| 76.2 | 0 | 0 | 0 |

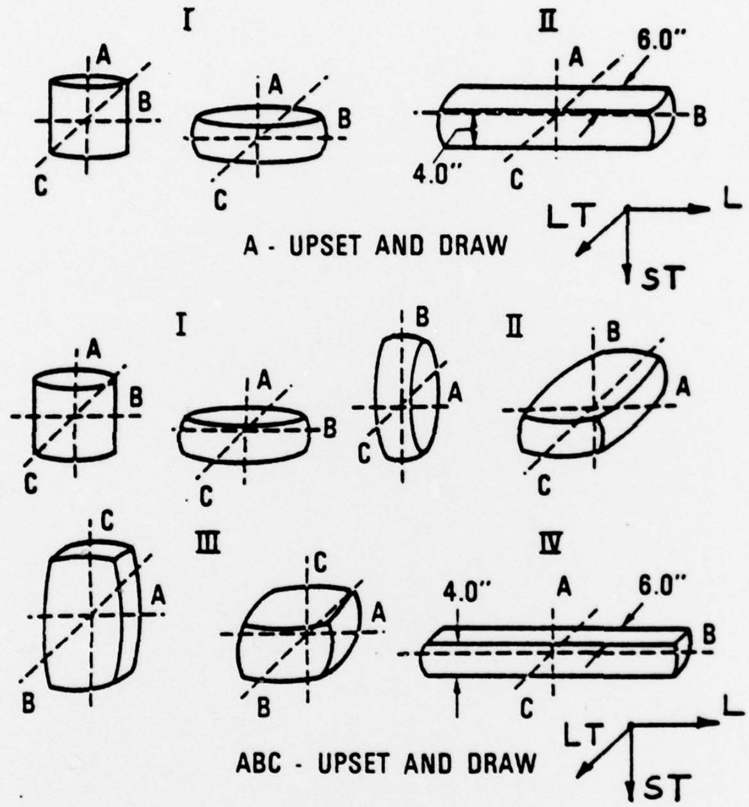



Figure 1. The two 'upset and draw' modes of deformation performed on hot compacted powder billets (5).

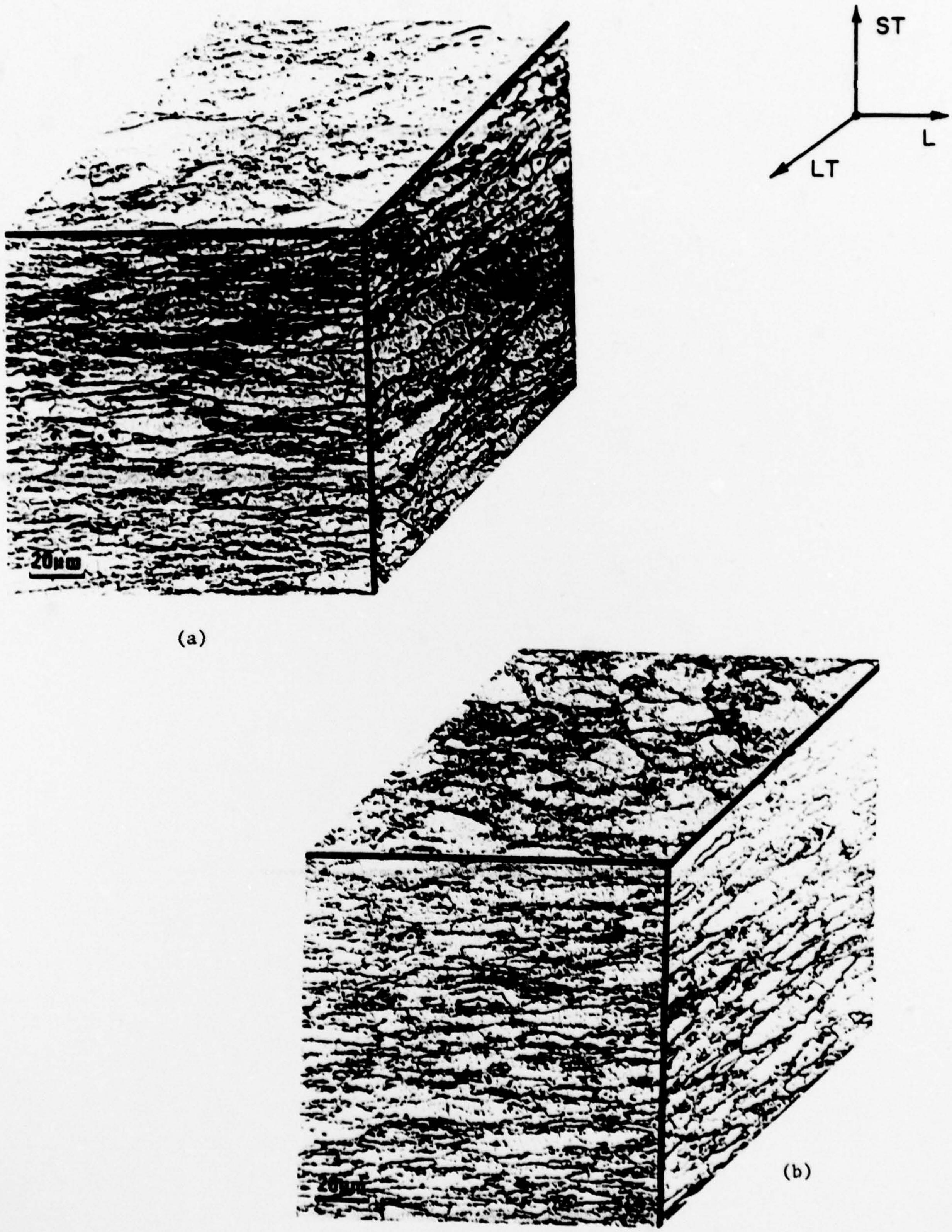
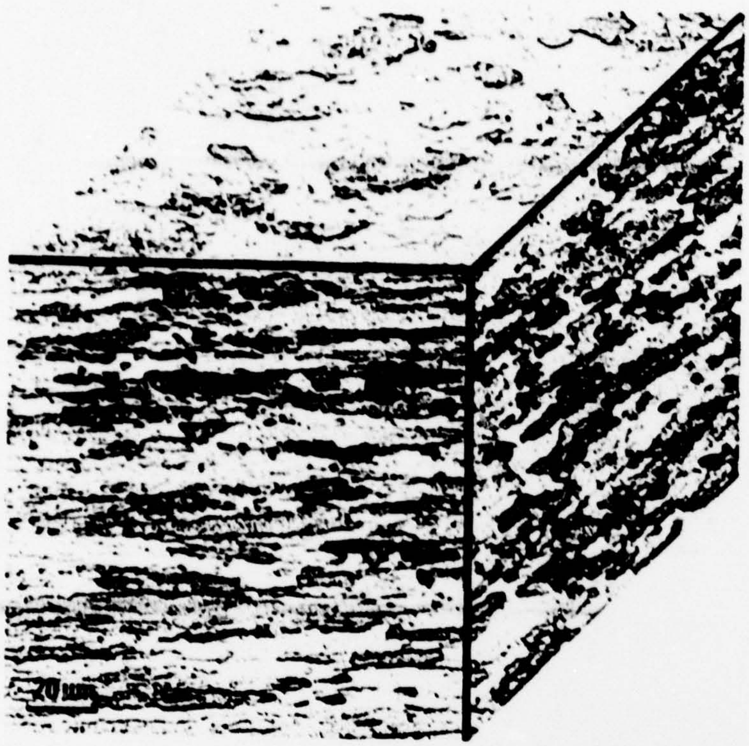
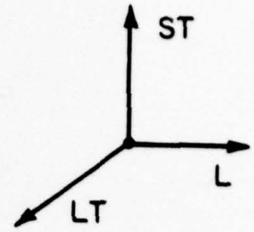



Figure 2. Microstructure of upset and drawn billets; 0% Co.
(a) A process; (b) ABC process.

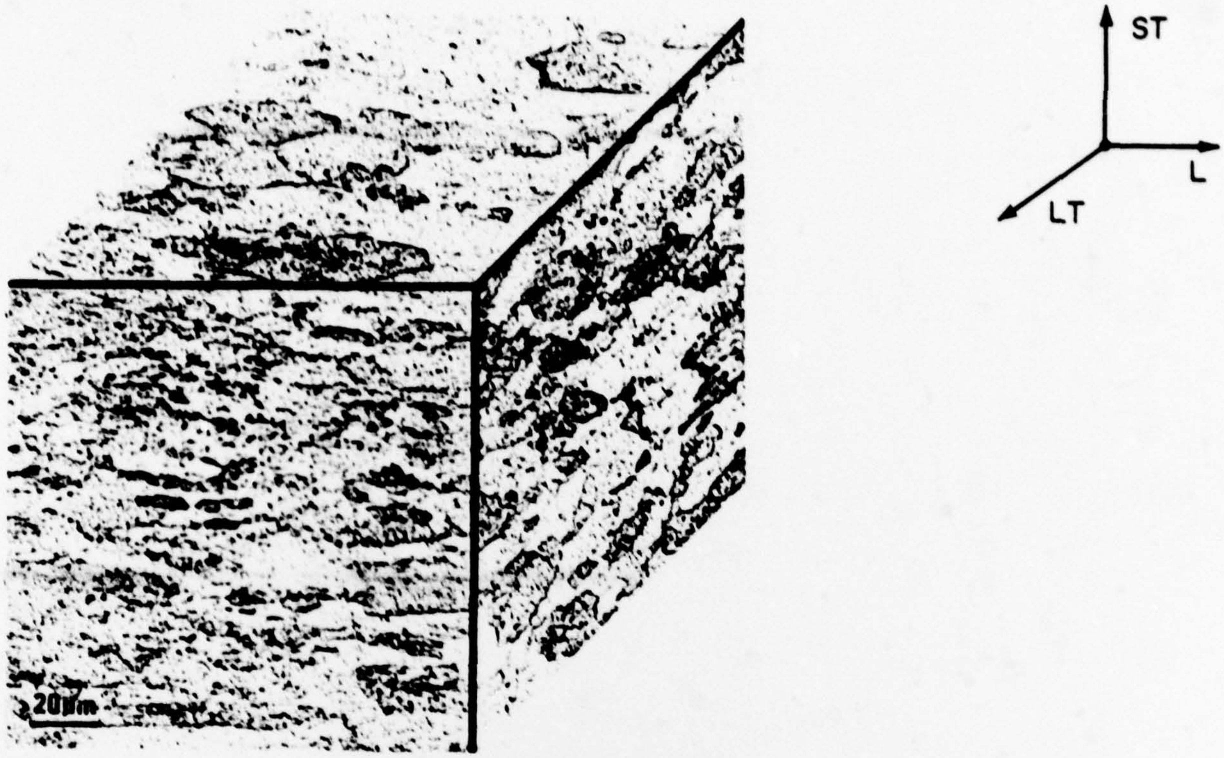


(a)




(b)

Figure 3. Microstructure of upset and drawn billets; 0.4% Co.
(a) A process; (b) ABC process.

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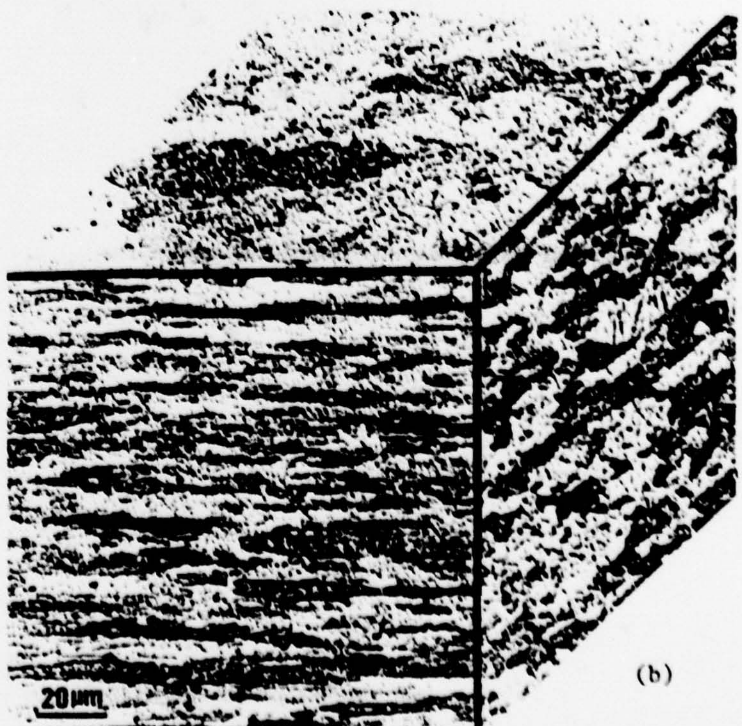
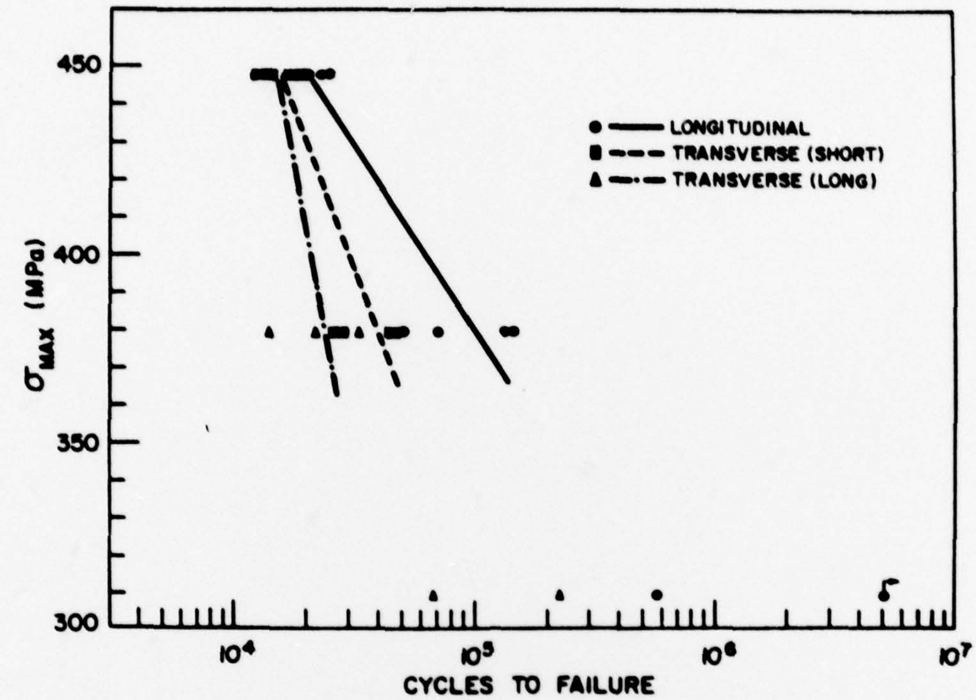



(b)

Figure 4. Microstructure of upset and drawn billets; 0.8% Co.
(a) A process; (b) ABC process.

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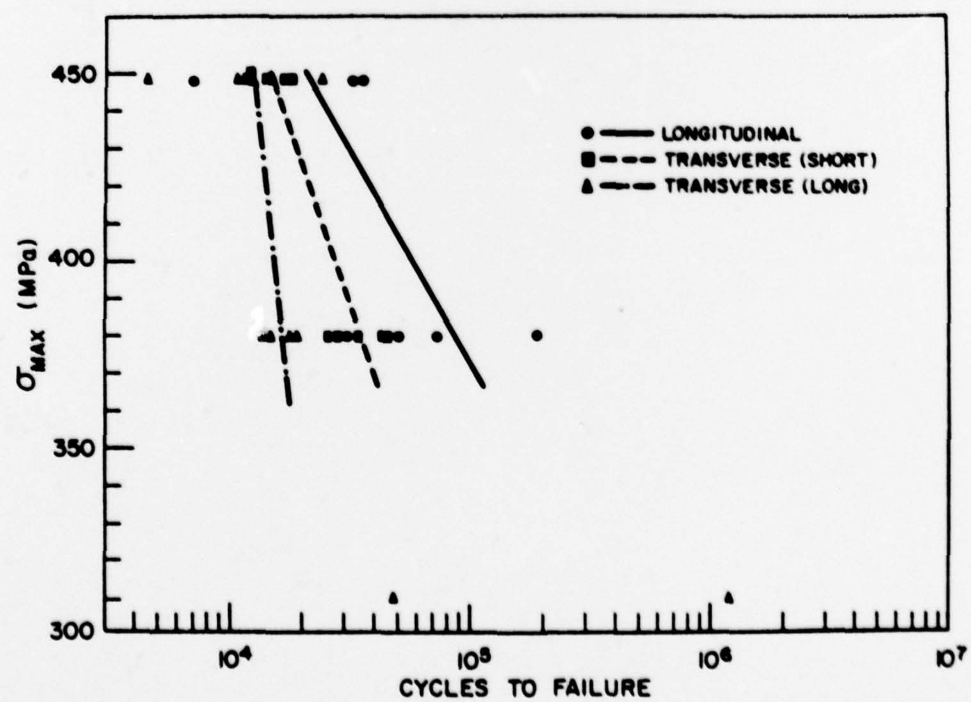
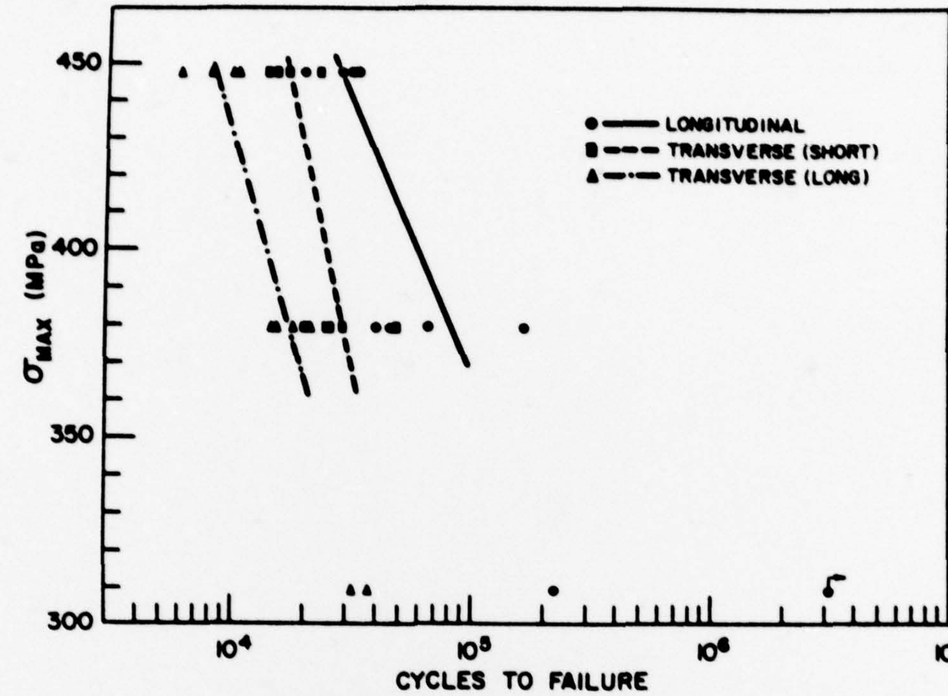



(b)

Figure 5. Tension-tension S-N curves (R = 0.1); 0% Co.
(a) A process; (b) ABC process.

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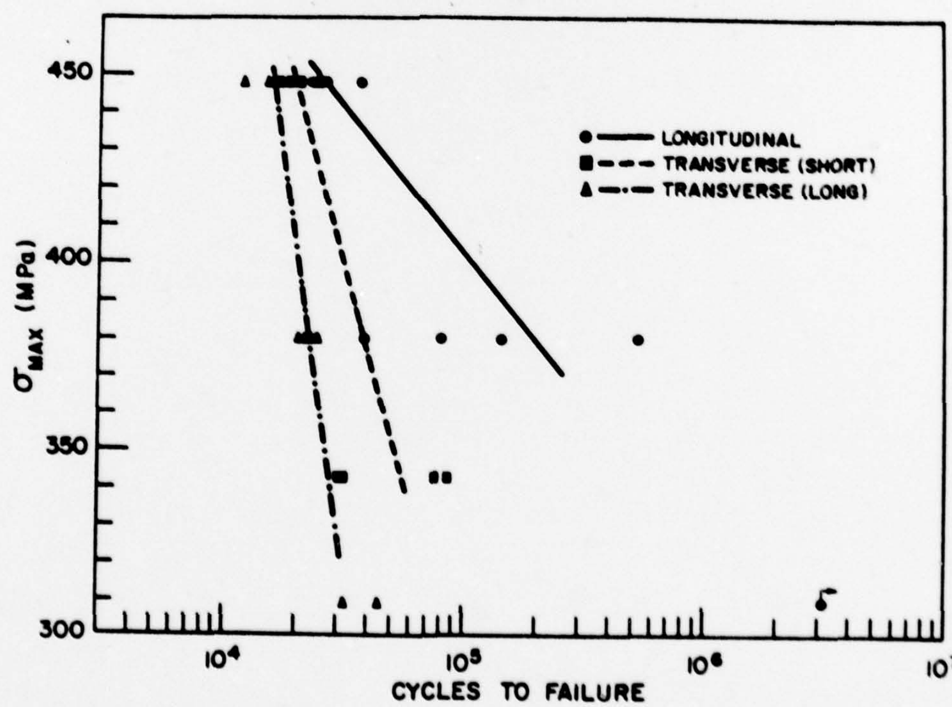


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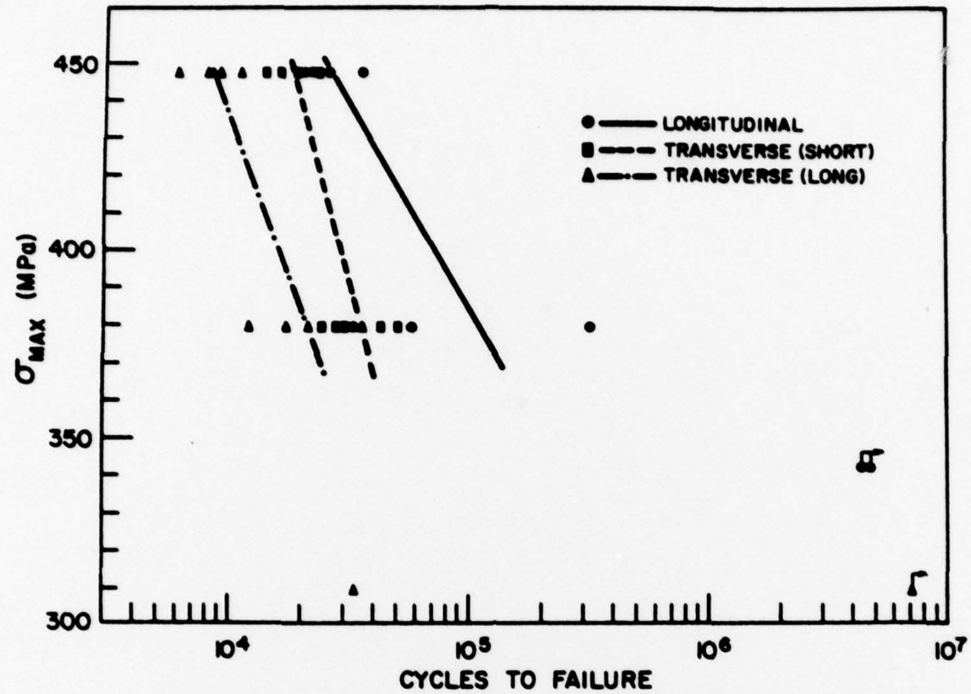
Figure 6. Tension-tension S-N curves (R = 0.1); 0.4% Co
(a) A process; (b) ABC process.

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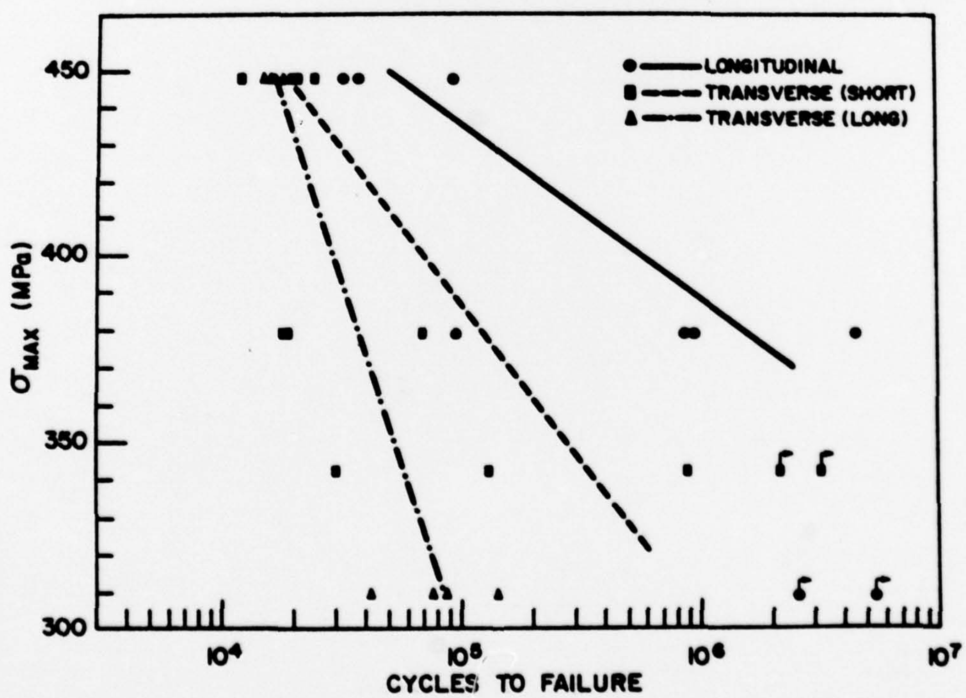



(b)

Figure 7. Tension-tension S-N curves (R = 0.1); 0.8 % Co.
(a) A process; (b) ABC process.

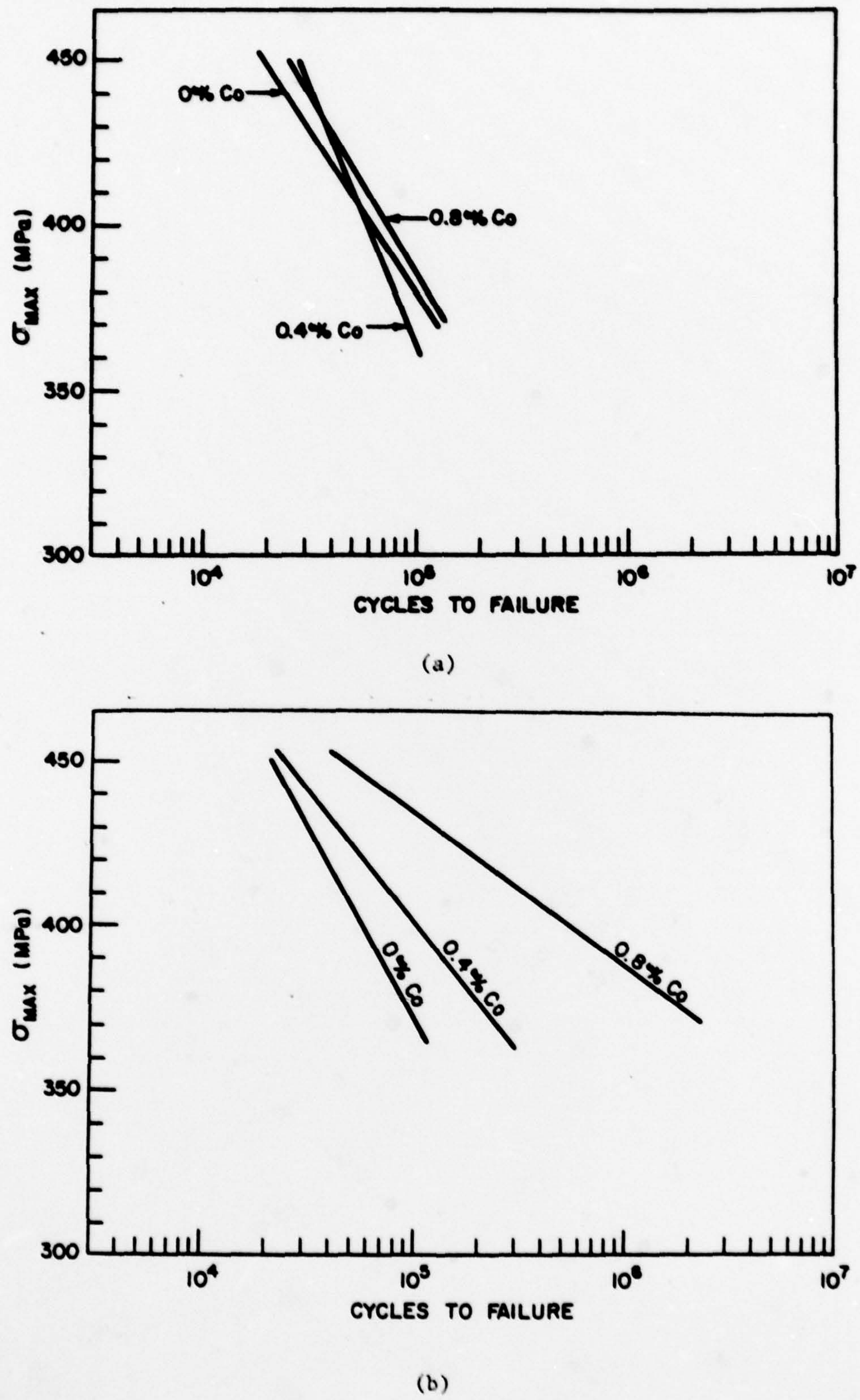



Figure 8. Effect of cobalt level on S-N response in the longitudinal (L) orientation; (a) A process; (b) ABC process.

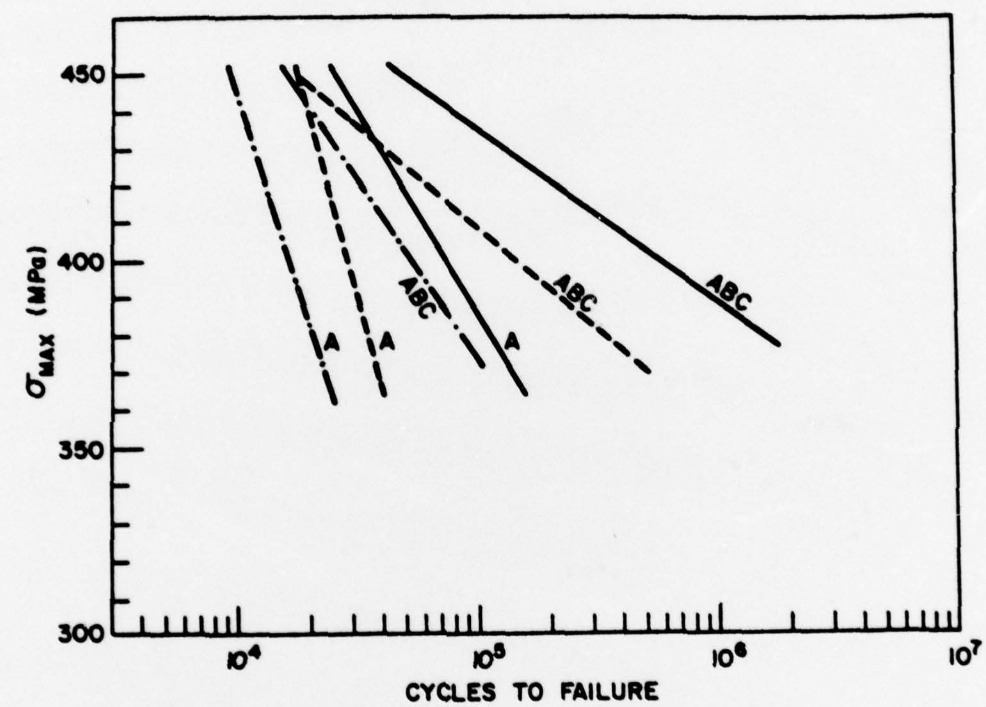
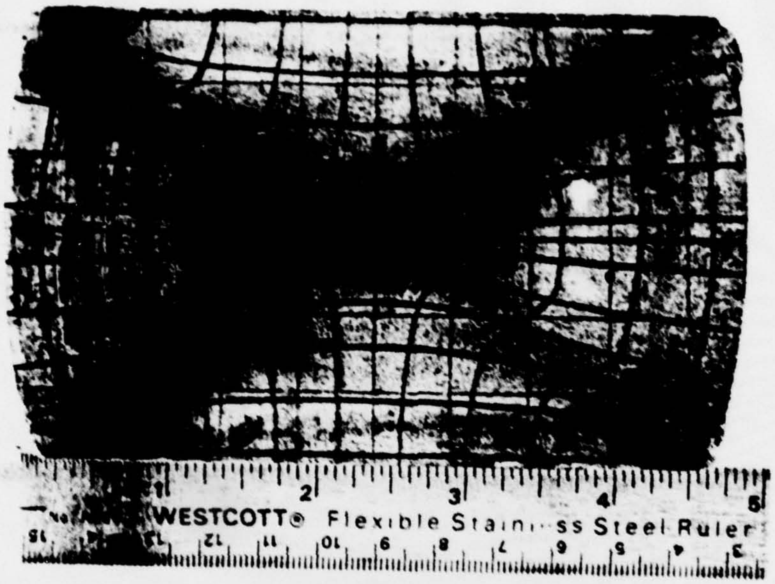
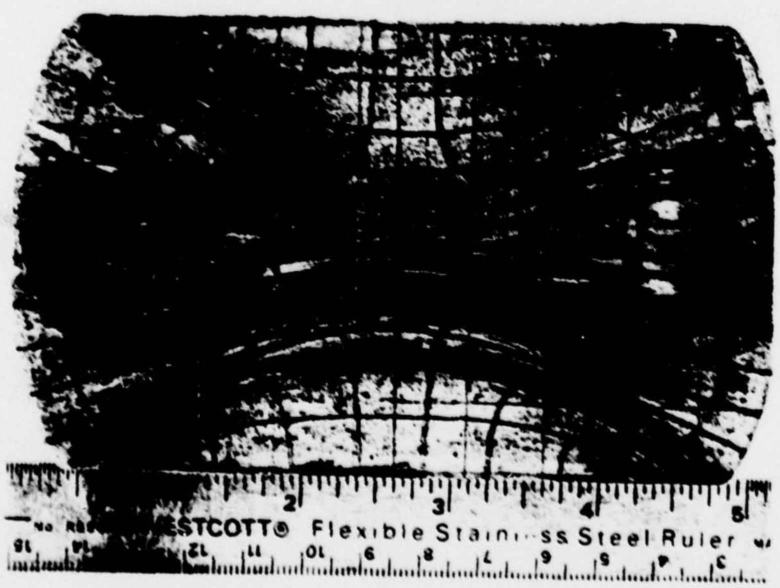



Figure 9. Effect of processing mode and specimen orientation on S-N response at a fixed cobalt level (0.8%)

(———— L; - - - - - - - - ST; —•—•—•—•— LT)




(a)




(b)

Figure 10. Grid shape after plane strain forging.
(a) Average $\varepsilon_h = 0.4$; (b) Average $\varepsilon_h = 0.7$.

## PERSONNEL

Professors M. J. Koczak and A. Lawley are the co-principal investigators on this program. Two graduate students, Harry W. Antes and Mario Rafalin, are engaged in research toward their respective Ph.D. degrees.

## PUBLICATIONS/DISSERTATIONS

"Fatigue of High Strength Aluminum-Alloy P/M Forgings" (M. Rafalin, M. J. Koczak and A. Lawley); Symposium on Thermomechanical Processing of Aluminum Alloys, AIME Fall Meeting (1978); to be published.

"Fatigue Behavior of Powder Metallurgy High-Strength Aluminum Alloys - The Role of Composition and Microstructure" - Ph.D. Topic (M. Rafalin).

"Role of Processing on the Fatigue Behavior of High Strength Powder Metallurgy Aluminum Alloys" - Ph.D. Topic (H. W. Antes).

## COUPLING ACTIVITIES

This program complements or couples with a number of recent and/or on-going AFOSR and AFML sponsored fatigue studies on ingot and P/M processed aluminum alloys. Liaison is maintained with principal investigator counterparts. The latter include: Professor E. A. Starke, Jr., Georgia Institute of Technology (corrosion fatigue); Dr. D. L. Davidson and Dr. J. Lankford, Southwest Research Institute (crack tip behavior); Dr. J. S. Santner and Mr. W. Griffith, AFML (microstructure and crack propagation); Professor M. E. Fine, Northwestern University (initiation and growth of microcracks); Professor H. Marcus, University of Texas (hold time effects on crack propagation); Dr. W. L. Otto, Alcoa (processing and crack propagation).

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Fatigue response in high strength powder metallurgy aluminum alloys is being evaluated; the primary objective is to establish and understand processing-microstructure-fatigue integrity relationships. The program includes stress-controlled low and high cycle response and a determination of crack propagation rates in both air and saline environments. In scope, there are two concurrent phases of research; in one, the combined effects of powder processing mode and cobalt level (0, 0.4, 0.8%) on fatigue are

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